

Charm production at HERA

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Abstract The ZEUS data on the charm structure function F_2^c at small x fit well to a single power of x , corresponding to the exchange of a hard pomeron that is flavour-blind. When combined with the contribution from the exchange of a soft pomeron, the hard pomeron gives a good description of elastic J/ψ photoproduction.

We have argued^[1] that Regge theory should be applicable to the structure function $F_2(x, Q^2)$ for small x and all values of Q^2 , however large, and have shown^[2] that indeed, in its very simplest form, it agrees extremely well with the available data. In order to fit the data, we introduced a second pomeron, the hard pomeron, with an intercept a little greater than 1.4; this is to be contrasted with the soft pomeron that is well-known from soft hadronic physics, whose intercept is close to 1.08.

Our main message in this paper is that the concept of the hard pomeron, with an intercept that is independent of Q^2 and is a little greater than 1.4, is supported by the recent ZEUS data^[3] for the charm structure function F_2^c . These data require only a hard pomeron: the coupling of the soft pomeron to charm is apparently very small. Hence the data for F_2^c are described by a single power of x . This is shown in figure 1, where the straight lines are

$$F_2^c(x, Q^2) = f_c(Q^2)x^{-\epsilon_0} \quad (1)$$

with $\epsilon_0 = 0.44$.

In our original fit^[1] to the data for the complete structure function $F_2(x, Q^2)$, we assumed a particular functional form for the coefficient function $f_0(Q^2)$ that multiplied $x^{-\epsilon_0}$. It had 4 parameters, and at large Q^2 it increased logarithmically with Q^2 . We have since found that a form with only 2 parameters works at least as well:

$$f_0(Q^2) = A_0 \left(\frac{Q^2}{Q^2 + Q_0^2} \right)^{1+\epsilon_0} \left(1 + \frac{Q^2}{Q_0^2} \right)^{\frac{1}{2}\epsilon_0} \quad (2)$$

With this form, $f_0(Q^2)x^{-\epsilon_0}$ behaves as a Q^2 -independent constant times ν^{ϵ_0} for large Q^2 . There is no general theory that explains this behaviour, though it has been predicted^[4] from the BFKL equation. As we have explained previously^[1], while the large- Q^2 behaviour of $f_0(Q^2)$ should surely be calculable from perturbative QCD, leading-order or next-to-leading-order approximations are inadequate and at present we do not know how to perform the necessary all-order resummations.

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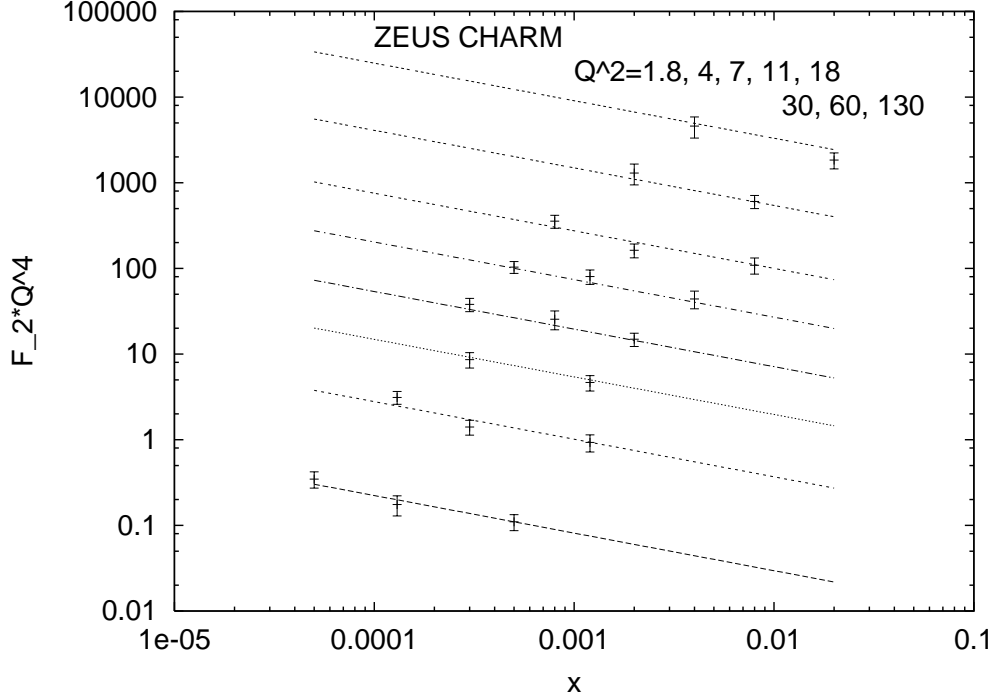


Figure 1: ZEUS data for $Q^4 F_2^c$, fitted to a single fixed power of x

The fit to F_2^c shown in figure 1 takes

$$f_c(Q^2) = A_c \left(\frac{Q^2}{Q^2 + Q_c^2} \right)^{1+\epsilon_0} \left(1 + \frac{Q^2}{Q_c^2} \right)^{\frac{1}{2}\epsilon_0} \quad (3)$$

In making our fit, we wrote the hard-pomeron contribution to the complete structure function $F_2(x, Q^2)$ as

$$(f_0(Q^2) + f_c(Q^2))x^{-\epsilon_0}$$

with $f_0(Q^2)$ and $f_c(Q^2)$ parametrised as in (2) and (3). Initially we imposed the constraint that at large Q^2 the hard pomeron coupling becomes flavour-blind, so that

$$A_c Q_c^{-\epsilon_0} = \frac{4}{7} A_0 Q_0^{-\epsilon_0} \quad (4)$$

The factor $\frac{4}{7}$ is calculated from squares of quark charges: $\frac{4}{9}/(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{1}{9})$. However, we found that, although it is not excluded that Q_c^2 is somewhat greater than Q_0^2 , the best fit has Q_c^2 close to Q_0^2 . That is, the data indicate that the coupling of the hard pomeron may be flavour-blind even for small Q^2 . This came as a surprise to us. Presumably it would imply that the same be true for the proton's bottom distribution.

With the constraint that $Q_c^2 = Q_0^2$, our fit to the ZEUS charm structure function data, together with nearly 600 data points for F_2 , corresponding to $x < 0.07$ and $0 \leq Q^2 \leq 2000 \text{ GeV}^2$, yielded a χ^2 of less than 1 per data point and

$$\epsilon_0 = 0.44 \quad A_0 = 0.025 \quad Q_0^2 = 8.1 \text{ GeV}^2 \quad (5)$$

More accurate data for F_2 are expected soon from HERA, and so the parameter values will change, as may the tentative conclusion that $Q_c^2 = Q_0^2$.

We have already shown^[2] that the two-pomeron picture gives a good fit to the total cross-section for elastic J/ψ photoproduction, $\gamma p \rightarrow J/\psi p$. There are now preliminary data^[5] on the differential cross section. As before^[2], we take the amplitude to be

$$T(s, t) = i \sum_{i=0,1} \beta_i(t) s^{e_i(t)} e^{-\frac{1}{2} \pi e_i(t)} \quad (6)$$

We normalise it so that $d\sigma/dt = |T|^2$. The differential-cross-section data now allow us to make a more informed choice of the pomeron coupling functions $\beta_i(t)$. Whereas in elastic pp scattering the data are in excellent agreement with the hypothesis^[6] that the soft-pomeron coupling function is proportional to the square $[F_1(t)]^2$ of the Dirac electric form factor, the data for $\gamma p \rightarrow J/\psi p$ rather need just $F_1(t)$. That is, the proton coupling to the pomeron (either soft or hard) is proportional to $F_1(t)$, but the pomeron- γ - J/ψ coupling apparently is flat in t . So we use

$$\begin{aligned} \beta_i(t) &= \beta_{0i} F_1(t) & i &= 0, 1 \\ F_1(t) &= \frac{4m^2 - 2.79t}{4m^2 - t} \frac{1}{(1 - t/0.71)^2} \end{aligned} \quad (7)$$

For the functions $e_i(t)$, which are related to the two pomeron trajectories by $\alpha_i(t) = 1 + e_i(t)$, we take

$$e_0(t) = 0.44 + \alpha'_0 t \quad e_1(t) = 0.08 + 0.25t \quad (8)$$

The soft-pomeron trajectory is familiar^[6], but the slope of the hard-pomeron trajectory is not known. The fit shown in figure 2 for the total cross-section is for

$$\alpha'_0 = 0.1 \quad \beta_{01}^2 = 24.6 \quad \beta_{00} = 0.038 \beta_{01} \quad (10)$$

We may obtain almost equally good fits to the total cross section if we make different choices of α'_0 , provided we adjust β_{00} and β_{01} :

$$\begin{aligned} \alpha'_0 = 0.0 & \quad \beta_{01}^2 = 26.4 & \quad \beta_{00} = 0.028 \beta_{01} \\ \alpha'_0 = 0.2 & \quad \beta_{01}^2 = 23.7 & \quad \beta_{00} = 0.046 \beta_{01} \end{aligned} \quad (11)$$

Note, though, that $\alpha'_0 = 0$ strictly is excluded, through t -channel unitarity^[7]. We show in figure 3 the differential cross-section for these three choices of α'_0 . It is evident that a choice somewhere near to 0.1 is a good one — though this cannot be a firm conclusion because the data are not good enough to confirm that (7) is necessarily the correct choice for $\beta_i(t)$. However, it is interesting that $\alpha'_0 = 0.1$ happens to be the value that is obtained by supposing that the hard pomeron trajectory is a glueball trajectory, so that there is a 2^{++} glueball of mass M given by $\alpha_0(M^2) = 2$. This corresponds to $M = 2370$ MeV, close to the mass of a 2^{++} glueball candidate reported by the WA102 collaboration^[8]. (Similarly, there is a 2^{++} glueball candidate at 1930 MeV, the correct mass for it to lie on the soft pomeron trajectory^[9].) The values of 0.0 and 0.2 for α'_0 are at the extremes which

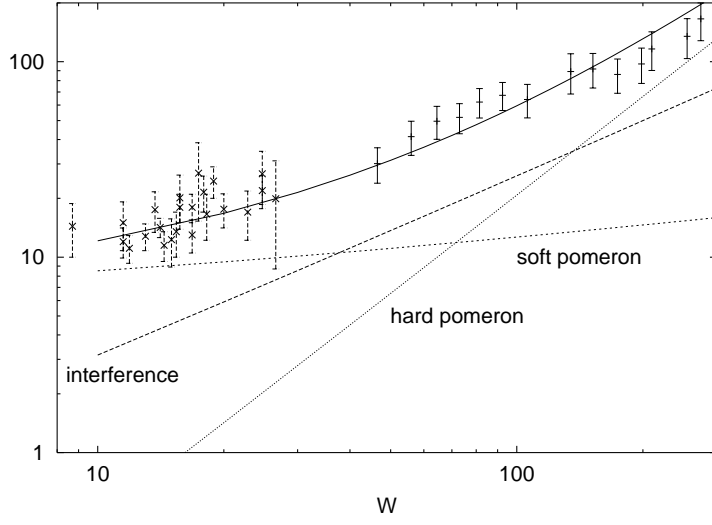


Figure 2: Fit to the total cross-section for elastic J/ψ photoproduction; the data are fixed-target and H1^[5]. The three contributions add up to the solid curve.

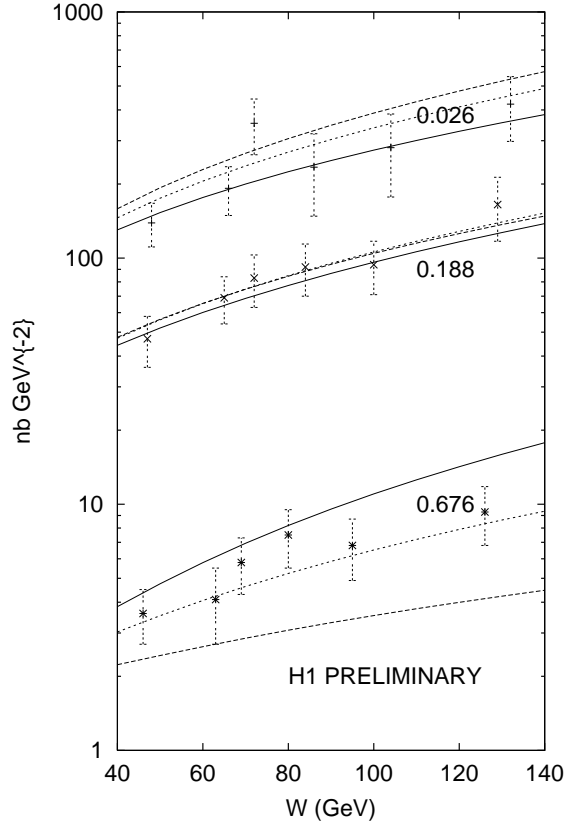


Figure 3: Fits to the differential cross-section for elastic J/ψ photoproduction for three t -values and hard pomeron slope $\alpha'_0 = 0$ (solid lines), $\alpha'_0 = 0.1$ (dotted lines) and $\alpha'_0 = 0.2$ (dashed lines)

the differential cross sections will accept, and limits of ~ 0.05 and 0.15 are more reasonable, with of course the above caveat on our choice of $\beta_i(t)$.

It is not excluded that there is also a hard-pomeron component present in elastic ρ photoproduction, though there the ratio β_{00}/β_{01} is very much smaller. It is possible that the value of β_{00} is the same in each case, up to a factor that reflects the different charges on the active quarks. In either case, ρ or J/ψ , if the data are parametrised by an effective power rise with energy W^δ , the increase^[10] of δ with Q^2 may be explained by the ratio β_{00}/β_{01} increasing with Q^2 .

We end with a comment that the surprisingly complete decoupling of the soft pomeron in the charm structure function presumably results from the limited overlap between the small $c\bar{c}$ pair and the extended soft pomeron. Justification for this view is the observation^[2] that the soft pomeron contribution to the proton structure function F_2 decreases with increasing Q^2 for $Q^2 \gtrsim 5 \text{ GeV}^2$. This can be quantified in the dipole-scattering approach of the Heidelberg model^[11], in which an explicit cut-off for the coupling of the soft pomeron to small dipoles simulates the phenomenological result of [2]. It might then be thought that exactly the same phenomenon would be observed in J/ψ photoproduction. However the fixed-target data collectively imply that there is some contribution at lower energies from the soft pomeron. This is confirmed by specific fits^[2,11] in the two-pomeron approach. A resolution of this apparent inconsistency can be obtained by postulating that there is an OZI-violating contribution to J/ψ photoproduction. Quite apart from the fact that the hadronic decays of the J/ψ are by this mechanism, there is clear evidence for an OZI-violating contribution to inclusive J/ψ production in hadronic interactions. At low energy the J/ψ production cross section from an antiproton beam is^[12] is several times greater than that from a proton beam. This shows that, in J/ψ production in hadronic interactions, there is a contribution from the valence quarks of the nucleon. The strength of the coupling of the J/ψ to a light quark-antiquark pair may be extracted from the production data^{[13][14][15]}, and is compatible with the hadronic decay rate of the J/ψ . The data on Υ production in hadronic interactions, in an equivalent region of x_F , imply that an OZI-violating mechanism is operable there also^[16]. It is not possible to quantify *a priori* the OZI-violating contribution to J/ψ photoproduction as it must arise from complicated $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ systems.

In conclusion, the fixed power of x found in the ZEUS data for the charmed structure function is most naturally explained by applying Regge theory at all Q^2 . This requires the introduction of a hard pomeron, just as we have found gives an excellent description of the total proton structure function F_2 and elastic J/ψ photoproduction.

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